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RESEARCH MEMORANDUM

INVESTIGATION AT SUPERSONIC SPEEDS OF THE EFFECT OF JET MACH NUMBER AND DIVERGENCE ANGLE OF THE NOZZLE UPON THE PRESSURE OF THE BASE ANNULUS OF A BODY OF REVOLUTION

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RESEARCH MEMORANDUM

INVESTIGATION AT SUPERSONIC SPEEDS OF THE EFFECT OF JET MACH NUMBER AND DIVERGENCE ANGLE OF THE NOZZLE UPON THE PRESSURE OF THE BASE ANNULUS OF A BODY OF REVOLUTION

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SUMMARY

An investigation has been conducted in the Langley 9-inch supersonic tunnel to determine the jet effects for varying jet Mach number and nozzle divergence angle upon the pressure on the base annulus of a model with a cylindrical afterbody. The tests were conducted over a wide range of jet static pressure ratios and at a Reynolds number of approximately 2.2×10^6 based on body length for free-stream Mach numbers of 1.62, 1.94, and 2.41. All testing was conducted with an artificially induced turbulent boundary layer along the model.

In the lower range of jet static pressure ratios, jet flow from a sonic or supersonic nozzle affected the pressure acting on the base annulus in essentially the same manner as shown in NACA RM E53H25 which covers jet static pressure ratios up to about 13. At higher pressure ratios the present results showed that the base pressure tends to level off with increasing jet static pressure ratio, and at the extreme static pressure ratios reached in tests with sonic nozzles the base pressure began to decrease. Except in the lower range of jet static pressure ratios, nozzle divergence angle generally had a larger effect on the base pressures than nozzle Mach number; the increase in base pressure for a change in divergence angle from 0° to 10° was small compared to the increase when the divergence angle was changed from 10° to 20°. A comparison of these and other data indicates that the effects of divergence angle were reduced when the ratio of jet exit diameter to base diameter was decreased. Jet Mach number effects increased with increase in stream Mach number.

INTRODUCTION

Several wind-tunnel investigations have been conducted in an effort to determine the effects of a propulsive jet on the aerodynamic characteristics of bodies of revolution. In reference 1 the jet effects on a parabolic body of revolution were considered. In references 2 and 3 investigations were made to determine the jet effects on base and afterbody pressures when the afterbody geometry was systematically varied. The studies of reference 4 have shown the jet effects for such variables as jet to base diameter, ratio of specific heats, and others. From reference 4 the effects of jet Mach number were indicated to be slight, but this indication was not conclusive. More recently the investigations of reference 5 have shown the effects of nozzle divergence angle and, to a lesser extent, the effects of jet Mach number upon the base pressure for hot jets.

The primary purpose of the present investigation was to observe the effects of jet Mach number and nozzle divergence angle on the base pressure for cold air jets. A secondary purpose of this investigation was to extend the base pressure variation with jet static pressure ratio to a range of jet pressure ratios considerably beyond that of the available data.

These tests were conducted at free-stream Mach numbers of 1.62, 1.94, and 2.41 and covered a range of static pressure ratios from jet off to 50 and higher for the sonic jets and from jet off to 6 and higher for the supersonic jets.

SYMBOLS

P_B	base pressure coefficient, $\frac{p_B - p_\infty}{q_\infty}$
d	diameter, in.
M	Mach number
p	static pressure, lb/sq in.
q	dynamic pressure, $\frac{\gamma p M^2}{2}$
θ	nozzle divergence angle, deg

γ	ratio of specific heats, 1.4 unless otherwise specified

Subscripts:

∞	stream conditions
j	jet conditions at nozzle exit
B	base of model

APPARATUS

Wind Tunnel

The Langley 9-inch supersonic tunnel is a continuous-operation, closed-circuit tunnel in which the pressure, temperature, and humidity of the enclosed air can be regulated. Different test Mach numbers are provided by interchangeable nozzle blocks which form test sections approximately 9 inches square. Eleven fine-mesh turbulence-damping screens are installed in the relatively large-area settling chamber ahead of the supersonic nozzle. The turbulence level of the tunnel is considered low, based on past turbulence level measurements. A schlieren optical system is provided for qualitative flow observation.

Models

A sketch illustrating the construction details and giving the pertinent dimensions of the model is shown in figure 1. The model is made of stainless steel and is a body of revolution consisting of a cylindrical afterbody with a 16.25 ogive nose. The model is supported by a 10-percent-thick side strut, the inside of which is hollow to facilitate the conduction of air to the jet and to act as a conduit for the pressure sensing tubes in the model. The effects of this strut on the base pressure have been found to be negligible by comparing the jet-off base pressure values of this investigation with the base pressure values for bodies of revolution having cylindrical afterbodies (no fins, ref. 6).

Ten nozzles were used in this investigation, two of which were sonic and eight supersonic. The two sonic nozzles (see fig. 1) differed in exit diameter (0.50 and 0.75 inch) only. This was accomplished by drilling and reaming the smaller diameter to the larger diameter. Six of the supersonic nozzles (see fig. 2) were conically divergent nozzles having a ratio of jet exit diameter to base diameter d_j/d_B equal to 0.75 and designed for exit Mach numbers of 2.50, 3.00, and 3.50 for two divergence angles θ of 10° and 20°. The other two supersonic nozzles had zero divergence angle and design Mach numbers equal to 3.00, based on area ratio only. One of these nozzles (nozzle A) had a contour which was found in a previous investigation to give essentially isentropic flow and an exit Mach number of 3.00. The other nozzle was a $M_j = 3.00$, $\theta = 20^{\circ}$ conical nozzle modified to a circular-arc-contour nozzle. The construction details and pertinent dimensions of all the supersonic nozzles are given in figure 2 and a typical installation is shown in figure 1.

TESTS AND PROCEDURE

All tests were conducted at a tunnel stagnation pressure of approximately one atmosphere for free-stream Mach numbers of 1.62, 1.94, and 2.41 and at a Reynolds number of approximately 2.2×10^{6} based on body length. During the tests the dewpoint in the tunnel was kept sufficiently low to insure negligible effects of condensation.

Throughout the test program a turbulent boundary layer over the model was maintained by use of an approximately 1/8-inch-wide transition strip as shown in figure 1. The base pressure measurements were made over a range of jet static pressure ratios as follows: for the sonic nozzles, jet off to $\frac{p_j}{p_\infty} = 48$ at $M = 1.62$, to $\frac{p_j}{p_\infty} = 76$ at $M = 1.94$, and to $\frac{p_j}{p_\infty} = 161$ at $M = 2.41$; for the supersonic nozzles, jet off to $\frac{p_j}{p_\infty} = 5.6$ at $M = 1.62$, to $\frac{p_j}{p_\infty} = 7.6$ at $M = 1.94$, and to $\frac{p_j}{p_\infty} = 18$ at $M = 2.41$. The difference in the base pressure measurements of the four orifices was found to be no more than that common to tests of this type (see ref. 3); therefore, an average value of the measurements from the four orifices was taken. Throughout the test program the model was under schlieren observation and a representative number of photographs were taken.

PRECISION

During this investigation, zero yaw and pitch of the model were maintained within $\pm 0.15^{\circ}$. Previous measurements of the flow angularity in the tunnel test section have shown negligible deviations. The free-stream Mach number is estimated to be within ± 0.01, based on past surveys of the tunnel airstream. The base pressure coefficient for a given orifice was accurate to within approximately ± 0.003.

The estimated accuracy of the jet stagnation pressure is approximately ±0.01 inch of mercury below an absolute pressure of 70 inches of mercury and ±0.50 inch of mercury above this absolute pressure.

RESULTS AND DISCUSSION

The behavior of the annular base pressure is discussed here in two parts. The initial part covers the variation of base pressure coefficient with static pressure ratio for the sonic jets. The second part is concerned with the variation of base pressure coefficient with static pressure ratio for the supersonic jets. Jet Mach number and nozzle divergence angle are the primary variables discussed.

Sonic Jets

The data for the sonic jets are presented in figures 3(a), 3(b), and 3(c) where base pressure coefficient is shown as a function of jet static pressure ratio for three free-stream Mach numbers of 1.62, 1.94, and 2.41, respectively. The base pressure coefficients indicated on the ordinate represent the values for the jet-off condition. Values of jet static pressure ratio of the order of 0.6 and lower have no real meaning since the nozzle is not started; consequently, these values serve only to establish a trend in base pressure coefficient.

For the lower jet static pressure ratios the variation of the base pressure with jet static pressure ratio is essentially the same as was found in references 2, 3, and 4 which cover jet static pressure ratios up to about 13. At higher pressure ratios the base pressure continues to increase and tends to level off with increasing jet static pressure ratio. At $M_\infty = 2.41$ the data for $\frac{d_j}{d_B} = 0.50$ increase with increasing jet static pressure ratio to a maximum at $\frac{p_j}{p_\infty}$ of approximately 141 and then decrease (see fig. 3(c)).

The effect of stream Mach number on the base pressure may be observed by comparing figures 3(a), 3(b), and 3(c). Increasing the stream Mach number causes an overall reduction in the base pressures with the spread between the data for the larger and smaller diameter exits also being reduced. The investigation of reference 4 showed a similar trend.

Supersonic Jets

The variation of base pressure coefficient with jet static pressure ratio as well as the effect of stream Mach number for the supersonic jets, with the exclusion of the circular-arc nozzle, is shown in figure 4. Portions of the curves for the sonic jet $\left(\frac{d_j}{d_B} = 0.75\right)$ are reproduced in each figure for comparison. The effect of stream Mach number and, in the lower range of jet static pressure ratios, the effect of jet static pressure ratio are essentially the same as those discussed previously for sonic jets. At higher pressure ratios, the base pressure coefficient shows a tendency to level off with increasing jet static pressure ratio. The pressure ratios below approximately 0.05 have no real meaning and the data in this portion of the curves are indicative of trend only. For the supersonic jet, the base pressure begins to increase at a value of $\frac{p_j}{p_\infty}$ lower than that for the sonic jet as might be expected from the variation in the value of $\frac{p_j}{p_\infty}$ for starting with M_j. At higher static pressure ratios (0.4 and higher), depending on stream Mach number, a slight "hump" in the data may be observed. This "hump" may be due to the fact that small changes in static pressure ratio do not produce any appreciable change in base pressure coefficient because the expansion angle of the outer stream at the edge of the base and the expansion angle of the jet flow at the lip of the nozzle are approximately equal in this range of jet static pressure ratios. From an overall viewpoint, the base pressure coefficients for the sonic nozzle are higher at all stream Mach numbers than for the $M_j = 3.00$ supersonic nozzle with the same divergence angle $\theta = 0^\circ$ and exit diameter; at $M_\infty = 1.94$ and 2.41 the base pressure coefficients for the sonic nozzle are, at the higher pressure ratios, even slightly higher than for the supersonic nozzles with a divergence angle of 10°.

From the same figure (fig. 4), an increase in jet Mach number is seen to have the effect of decreasing the base pressure (with the possible exception of the very low pressure ratios); this effect is small at $M_\infty = 1.62$ and increases as stream Mach number increases. This trend may be expected if the variations of pressure-rise coefficient and critical turning angle with Mach number (discussed in detail in ref. 6) are considered.

From figure 4, it may be observed that, except in the lower range of $\frac{p_j}{p_\infty}$, increasing the jet divergence angle generally has a much greater effect on the base pressure than changing the jet Mach number; the increase in base pressure when the divergence angle is increased from 0° to 10° is small compared to the large increase in base pressure when the divergence angle is increased from 10° to 20°. It is interesting to note that the effects of jet divergence angle found in the present investigation for $M = 1.62$ are very similar to the hot jet results of reference 5 for a 10° boattail model at $M_{\infty} = 1.59$. The ratio of jet exit diameter to base diameter is very nearly the same for the models in the two investigations (about 0.65 for ref. 5 and 0.75 for these tests). From a comparison of the data of reference 5 for a zero boattail model $\left(\frac{d_j}{d_B} = 0.435\right)$ with the data of the present investigation, it appears that the effects of nozzle divergence angle are reduced when $\frac{d_j}{d_B}$ is decreased.

Schlieren studies of two conical nozzles with divergence angles of 10° and 20° and a jet Mach number of 2.50 are presented in figures 5(a) and 5(b) for a range of jet static pressure ratios. Comparison of the photographs for a static pressure ratio of 2.66 shows that there is an appreciable increase in the diameter of the jet in the plane of origin of the trailing shocks as divergence angle is increased. This increase in the diameter of the jet reduces the expansion of the free-stream flow about the edge of the base, thereby increasing the base pressure.

Using short supersonic nozzles having $\theta = 0^{\circ}$ can reduce or eliminate the shock at the exit for the design operating condition $\left(\frac{p_j}{p_{\infty}} = 1.0\right)$, thus reducing or eliminating interference on overhanging control surfaces. The circular-arc-contour nozzle, because of its simplicity in design and manufacture, is frequently proposed for this purpose. To obtain an idea of what might be expected from a contour of this type, tests were made of a circular-arc nozzle $(\theta = 0^{\circ})$ having a design area ratio for a Mach number of 3.00. The results of these tests are presented in figure 6 and, as a point of possible interest, are compared with the results for the nozzle having essentially isentropic flow (nozzle A, $M_j = 3.00$, $\theta = 0^{\circ}$). The values of $\frac{p_j}{p_{\infty}}$ for the circular-arc nozzle were computed for $M_j = 3.00$, although it is obvious that the actual value of M_j would be less and computed values of $\frac{p_j}{p_{\infty}}$ greater, accordingly. It follows that caution should be exercised in utilizing experimental data for design purposes when the design value of M_j is based on area ratio only.

Figures 7 and 8 present, respectively, a series of schlieren photographs of the flow exhausting from the circular-arc nozzle and the nozzle having a contour giving essentially isentropic flow. Comparison of the photographs illustrates the additional shocks and the complex flow that may be present in the jet of a circular-arc-contour nozzle.

CONCLUSIONS

An investigation has been conducted in the Langley 9-inch supersonic tunnel to determine the jet effect for varying jet Mach number and nozzle divergence angle on the pressure on the base annulus of a model with a cylindrical afterbody. The tests were conducted over a wide range of jet pressure ratios and at a tunnel stagnation pressure of approximately one atmosphere for free-stream Mach numbers of 1.62, 1.94, and 2.41. The following conclusions are indicated:

1. For the lower jet static pressure ratios the effect of jet flow from a sonic or supersonic nozzle on the base pressure was essentially the same as that described in NACA RM E53H25 which covers jet static pressure ratios up to about 13. At higher pressure ratios the present results showed that the base pressure tends to level off with increasing jet static pressure ratio, and at the extreme jet static pressure ratios reached in tests with sonic nozzles the base pressure began to decrease.

2. The effect of nozzle divergence angle generally had a larger effect on the base pressures than jet Mach number, with the possible exception of the lower range of static pressure ratios; the increase in base pressure for a change in divergence angle from 0° to 10° was small compared to the increase when the divergence angle was changed from 10° to 20°. Comparison of these and other data indicated that the effects of nozzle divergence angle were reduced when the ratio of jet exit diameter to base diameter was decreased.

3. The effects of jet Mach number increased with increase in stream Mach number.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 7, 1954.

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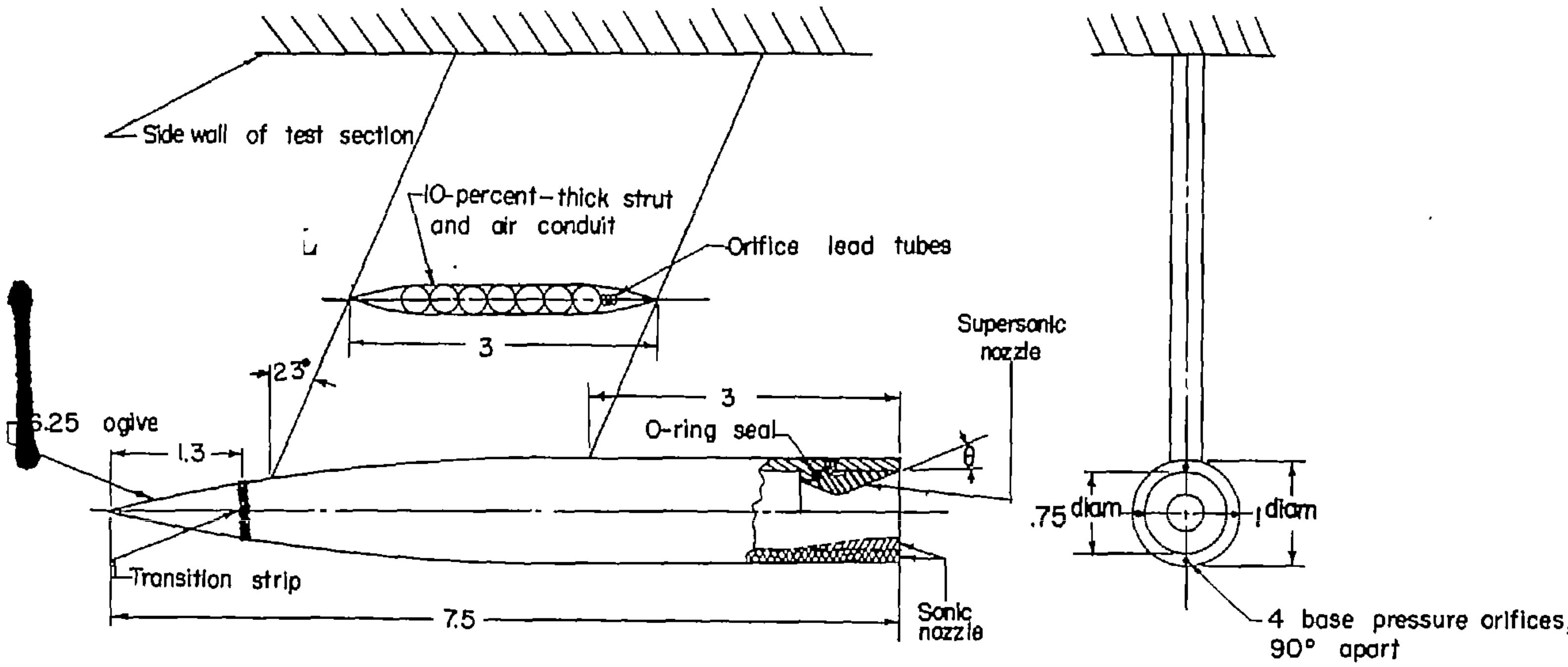

Jet effect model

Figure 1.- Drawing of model and typical installation of nozzle. All dimensions are in inches.

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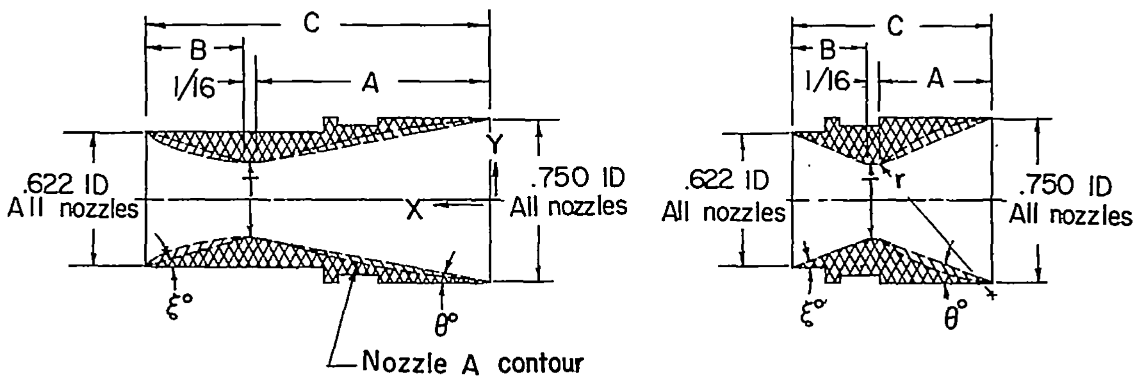

Design M	T	θ=10°, C=1.625 A	B	ξ
2.50	.462	.817	.745	6.13°
3.00	.364	1.093	.469	15.35°
3.50	.288	1.311	.252	33.55°

Conical nozzles

Design M	T	θ=20°, C=.938 A	B	ξ
2.50	.462	.396	.480	9.48°
3.00	.364	.530	.346	20.42°
3.50	.288	.635	.241	34.78°

Conical nozzles

Design M	T	θ=0°, C=.928 A	B	ξ	r
3.00	.364	.530	.346	20.42°	.816

Circular-arc nozzle, θ=0°

X	Y	X	Y	X	Y	X	Y
0	.371	.5	.313	1.0	.200	1.5	.242
.1	.364	.6	.294	1.1	.188	1.625	.312
.2	.355	.7	.273	1.2	.182		
.3	.345	.8	.249	1.3	.189		
.4	.330	.9	.224	1.4	.208		

Nozzle A contour, $\theta = 0°$, $M_{design} = 3.00$

Figure 2.- Nozzle details. All dimensions are in inches.

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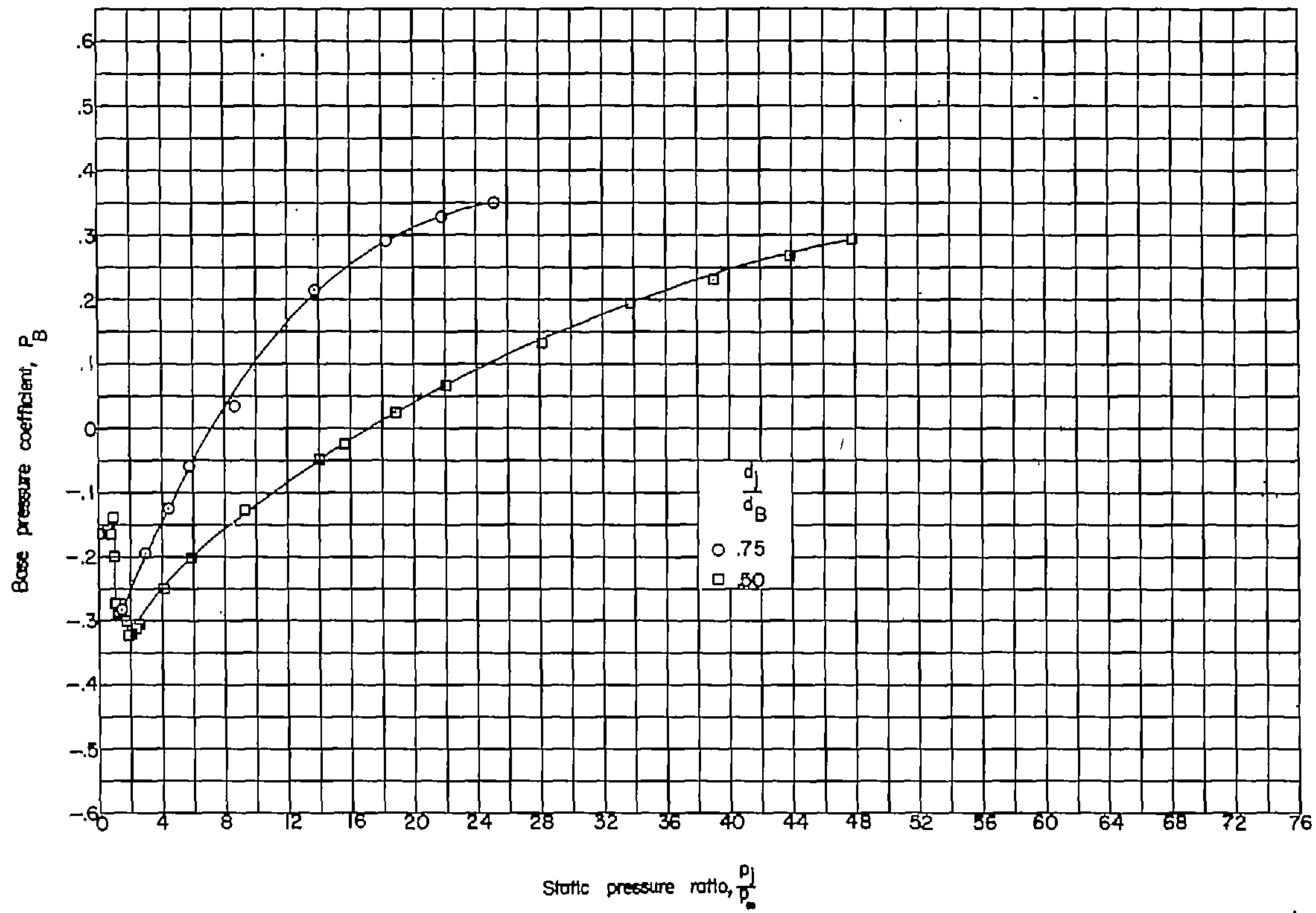

(a) $M_\infty = 1.62$.

Figure 3.- Variation of base pressure coefficient with static pressure ratio for a sonic nozzle with two different exit diameters.

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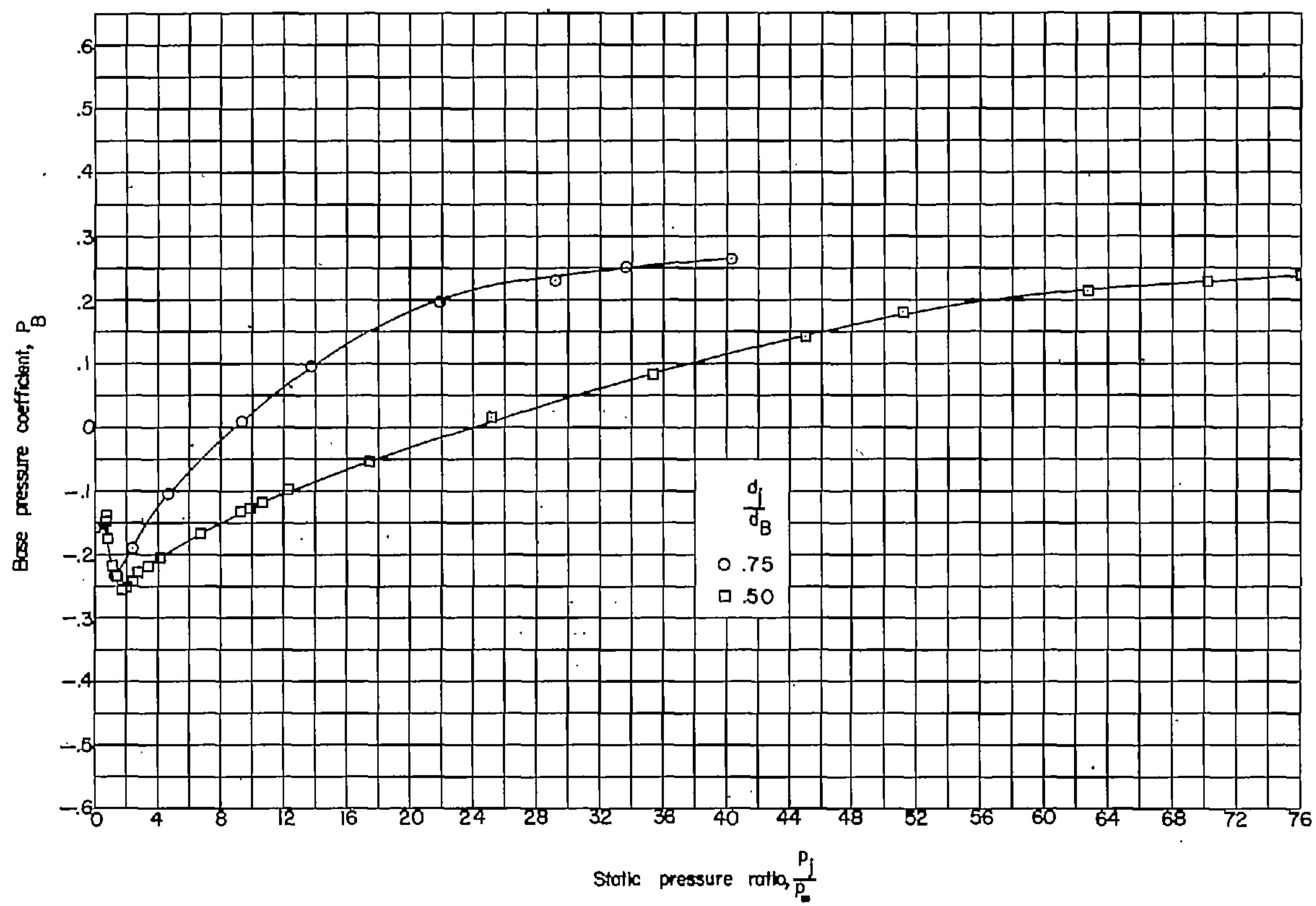

(b) $M_\infty = 1.94$.

Figure 3.- Continued.

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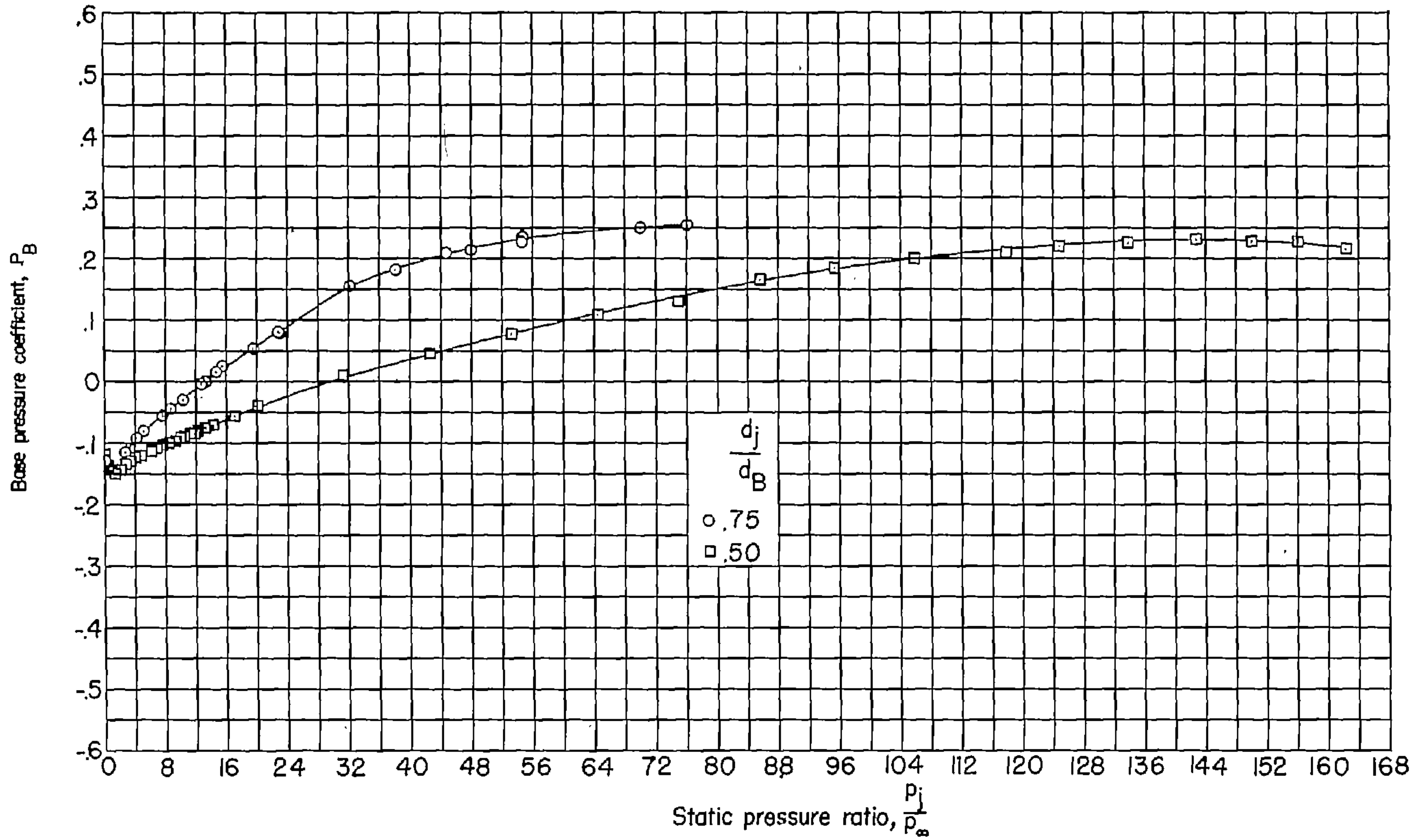
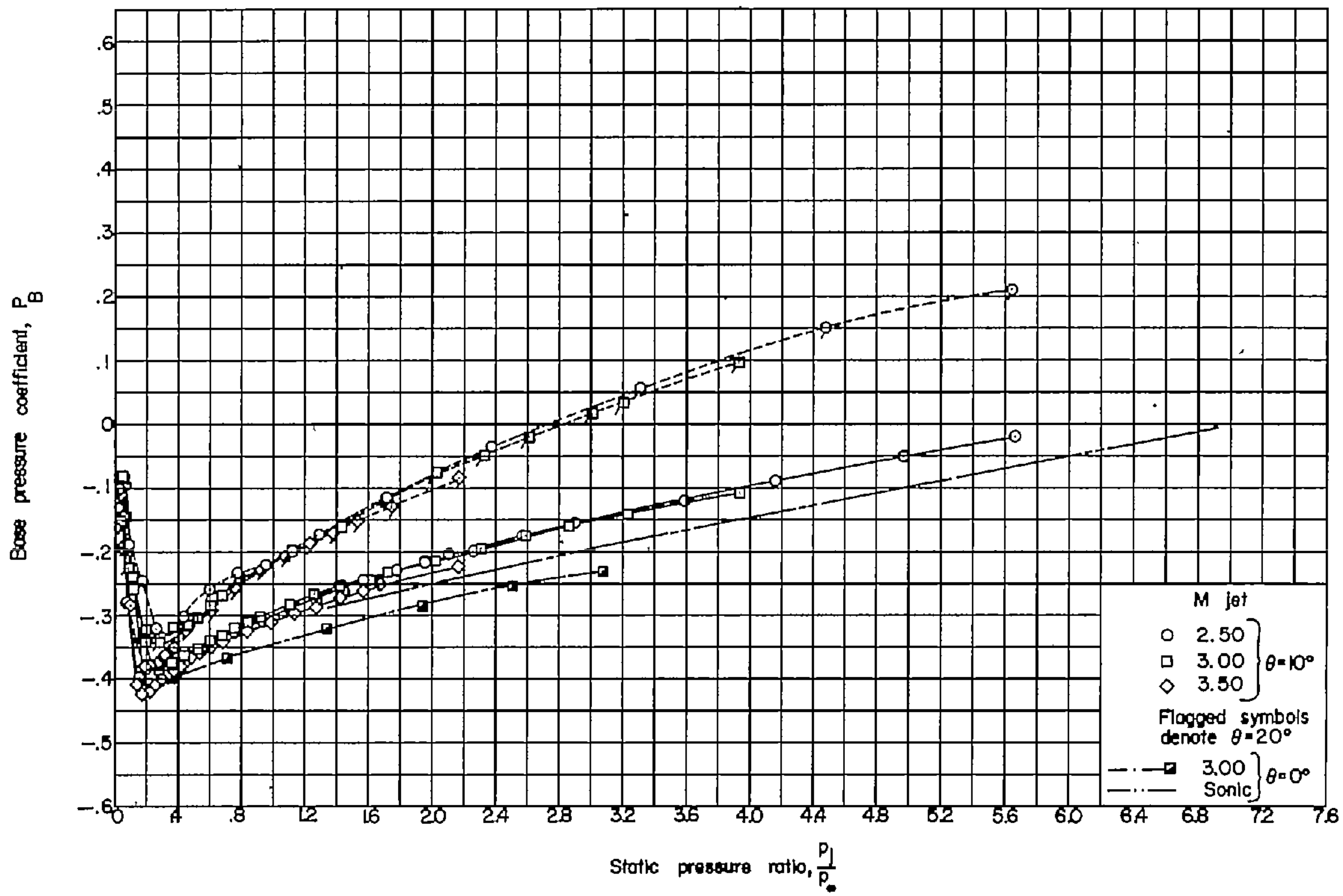


(c) $M_\infty = 2.41$.

Figure 3.- Concluded.



(a) $M_\infty = 1.62$.

Figure 4.- Variation of base pressure coefficient with static pressure ratio for several supersonic nozzles with varying jet Mach number and nozzle divergence angle.

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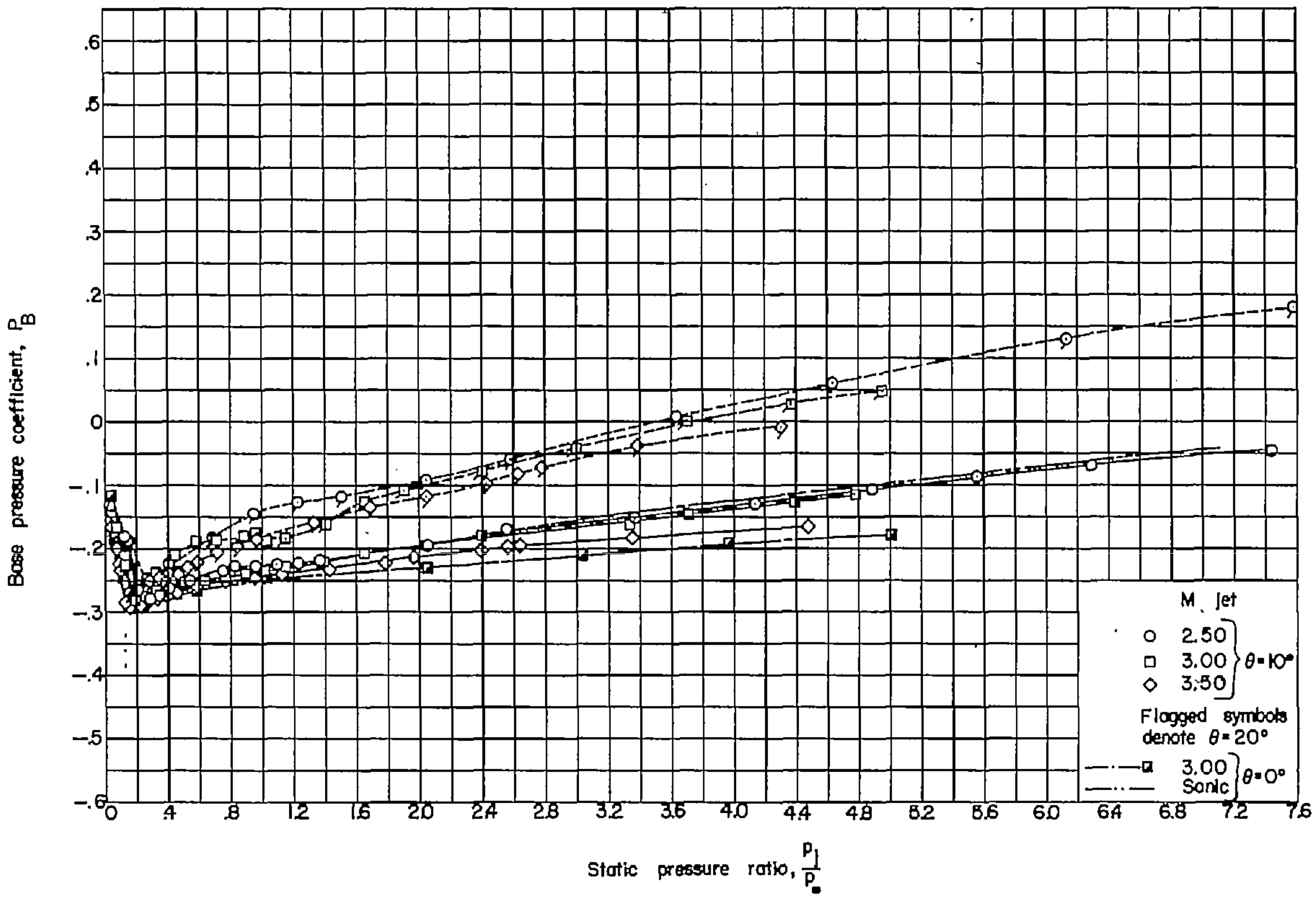

(b) $M_\infty = 1.94$.

Figure 4.- Continued.

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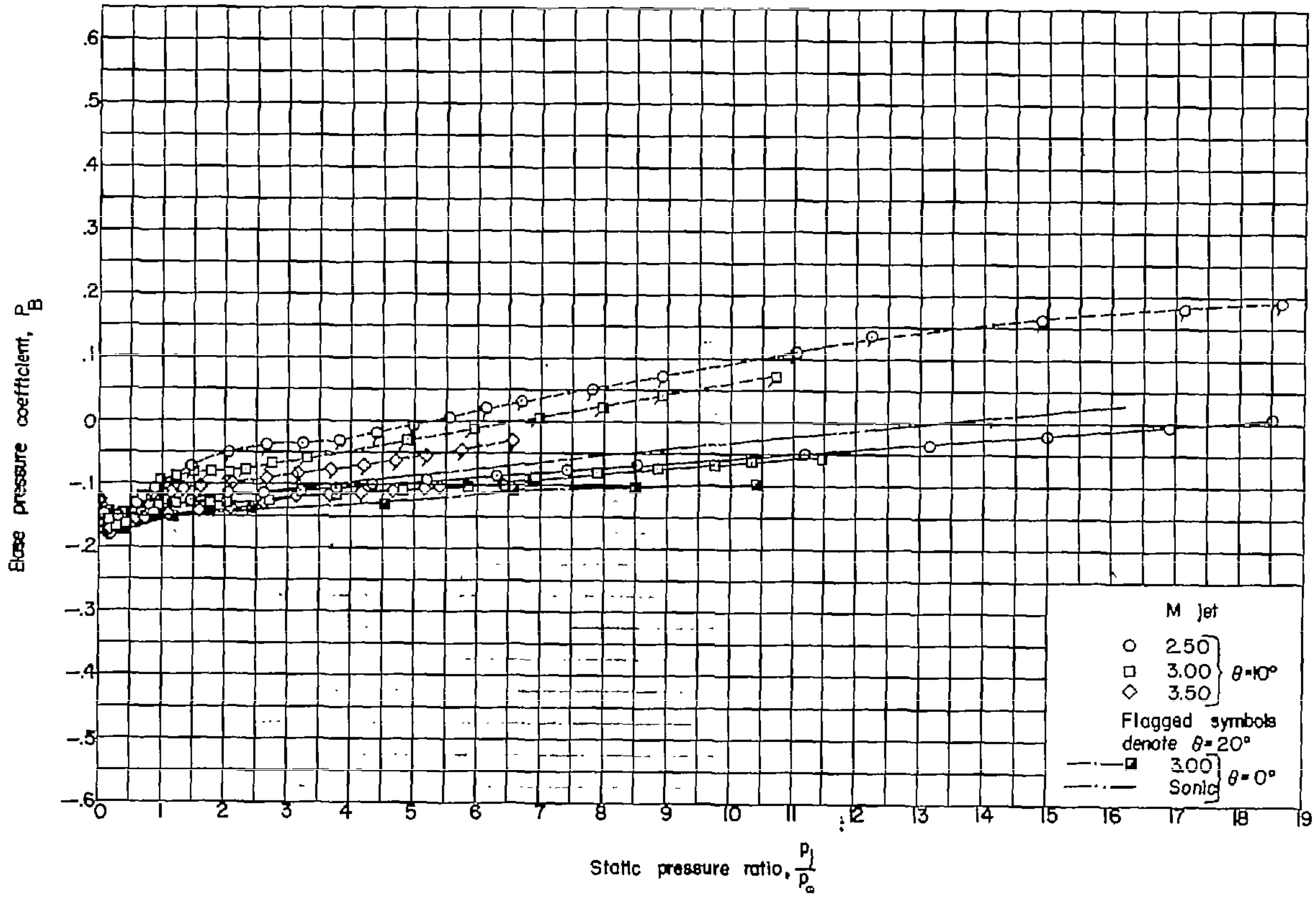
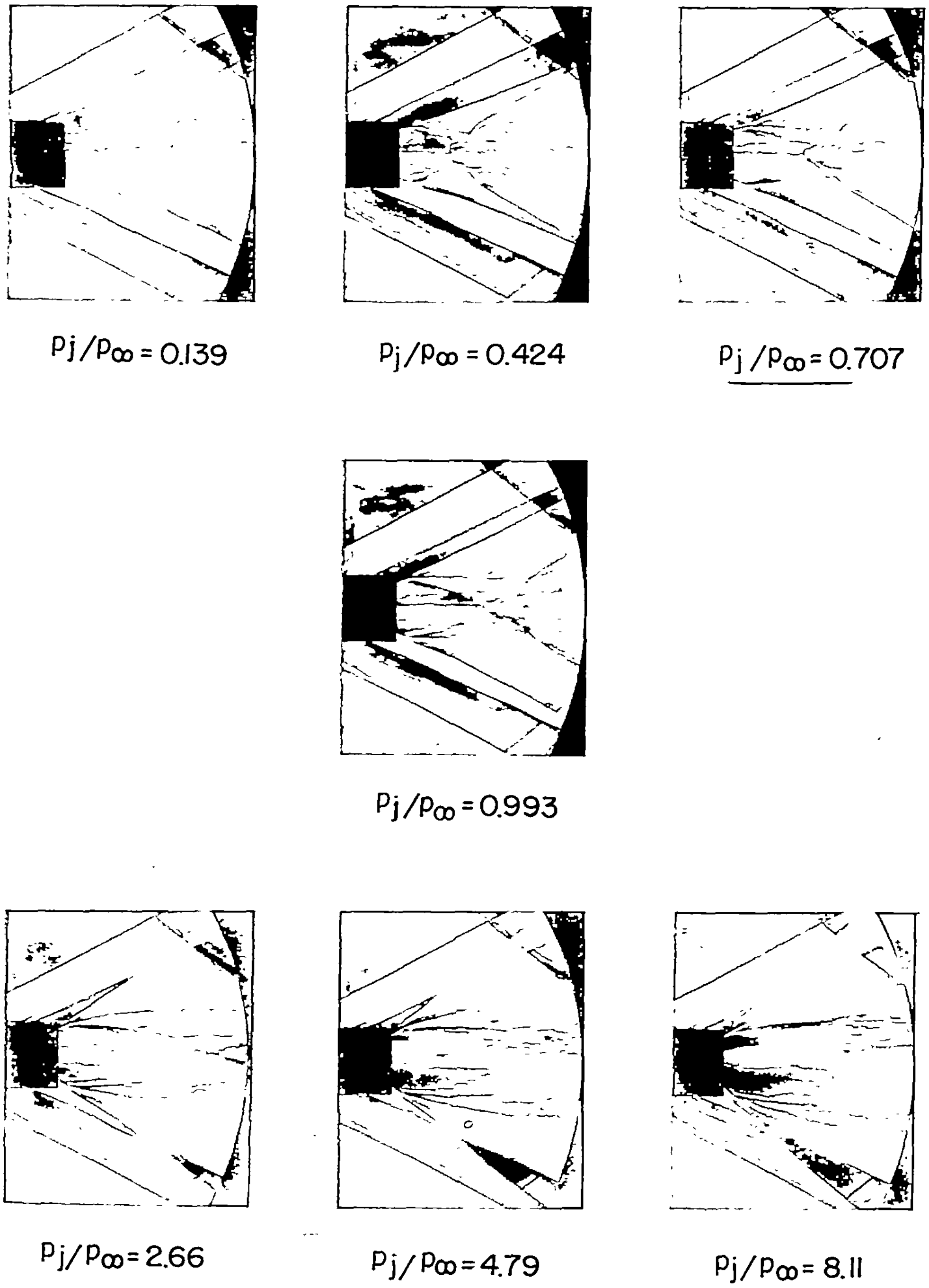


(c) $M_\infty = 2.41$.

Figure 4.- Concluded.



(a) $\theta = 10^{\circ}$.

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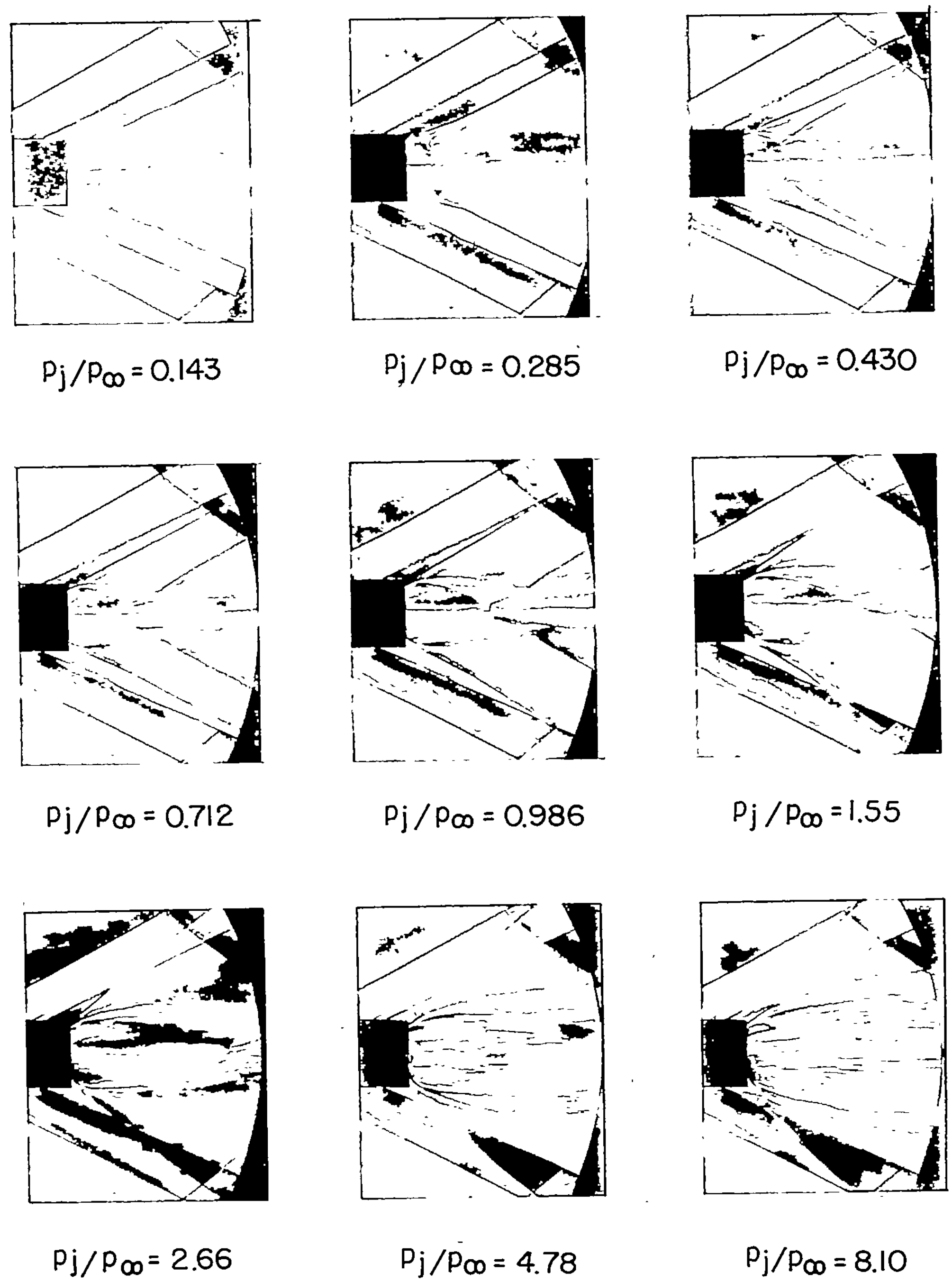
Figure 5.- Schlieren photographs of conically divergent nozzles of $M_j = 2.50$ at $M_\infty = 1.94$.



(b) $\theta = 20^{\circ}$. L-85655

Figure 5.- Concluded.

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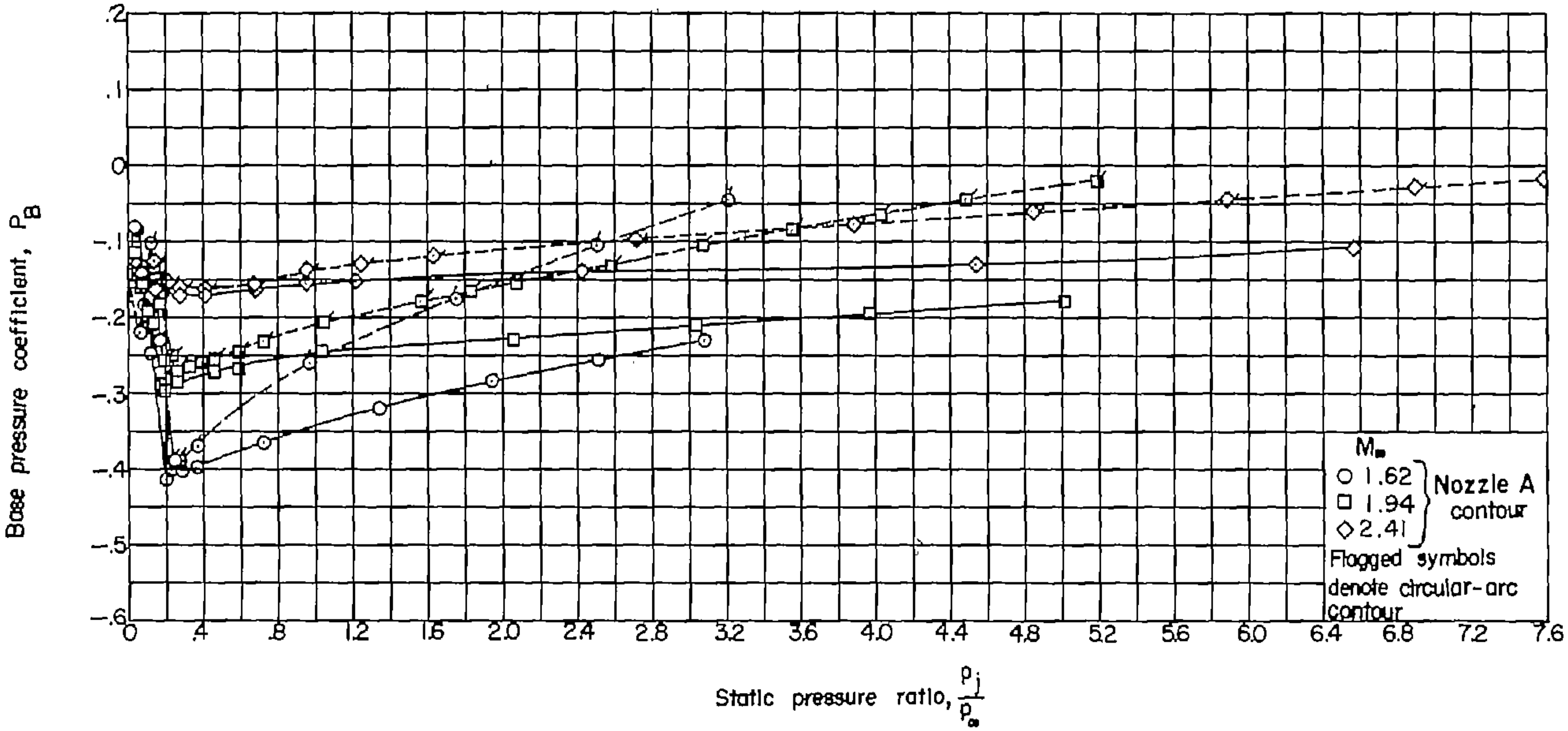

Figure 6.- Variation of base pressure coefficient with static pressure ratio for a short circular-arc-contour nozzle and a nozzle giving essentially isentropic flow with $M_j = 3.00$ and $\theta = 0^\circ$.

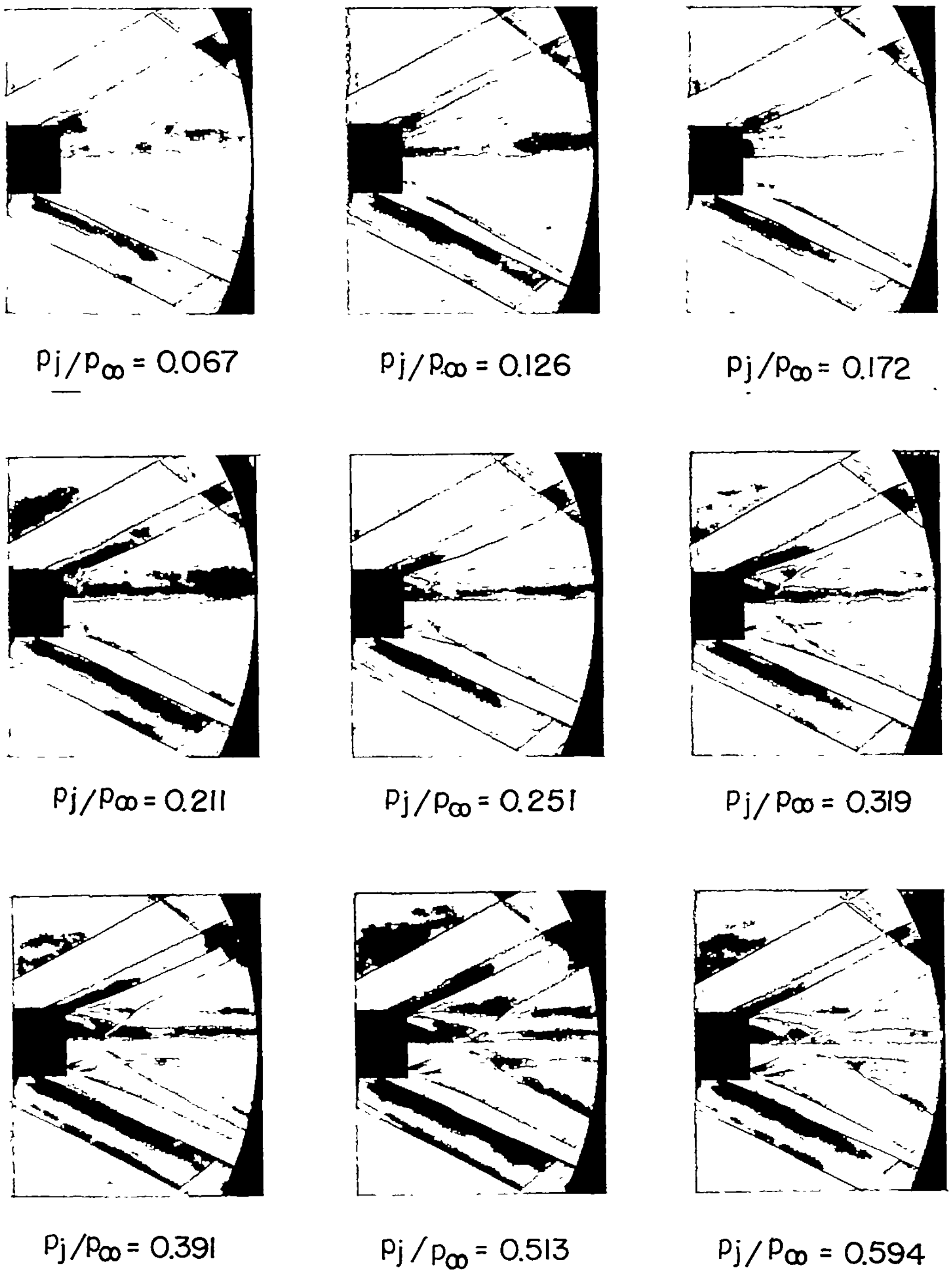

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Figure 7.- Schlieren photographs of a short circular-arc-contour nozzle with $M_j = 3.00$ and $\theta = 0^{\circ}$ at $M_\infty = 1.94$.

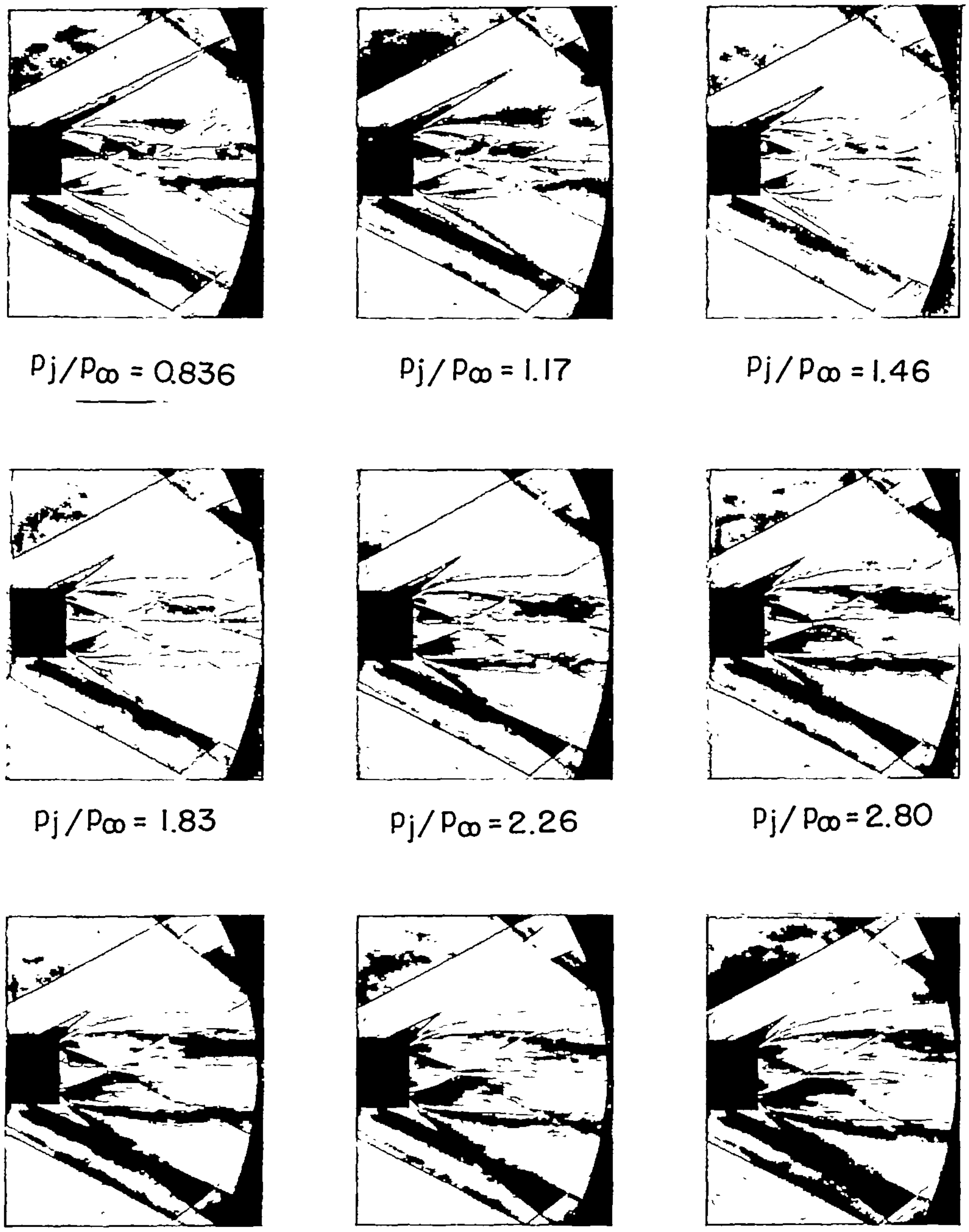

Figure 7.- Concluded. L-85657

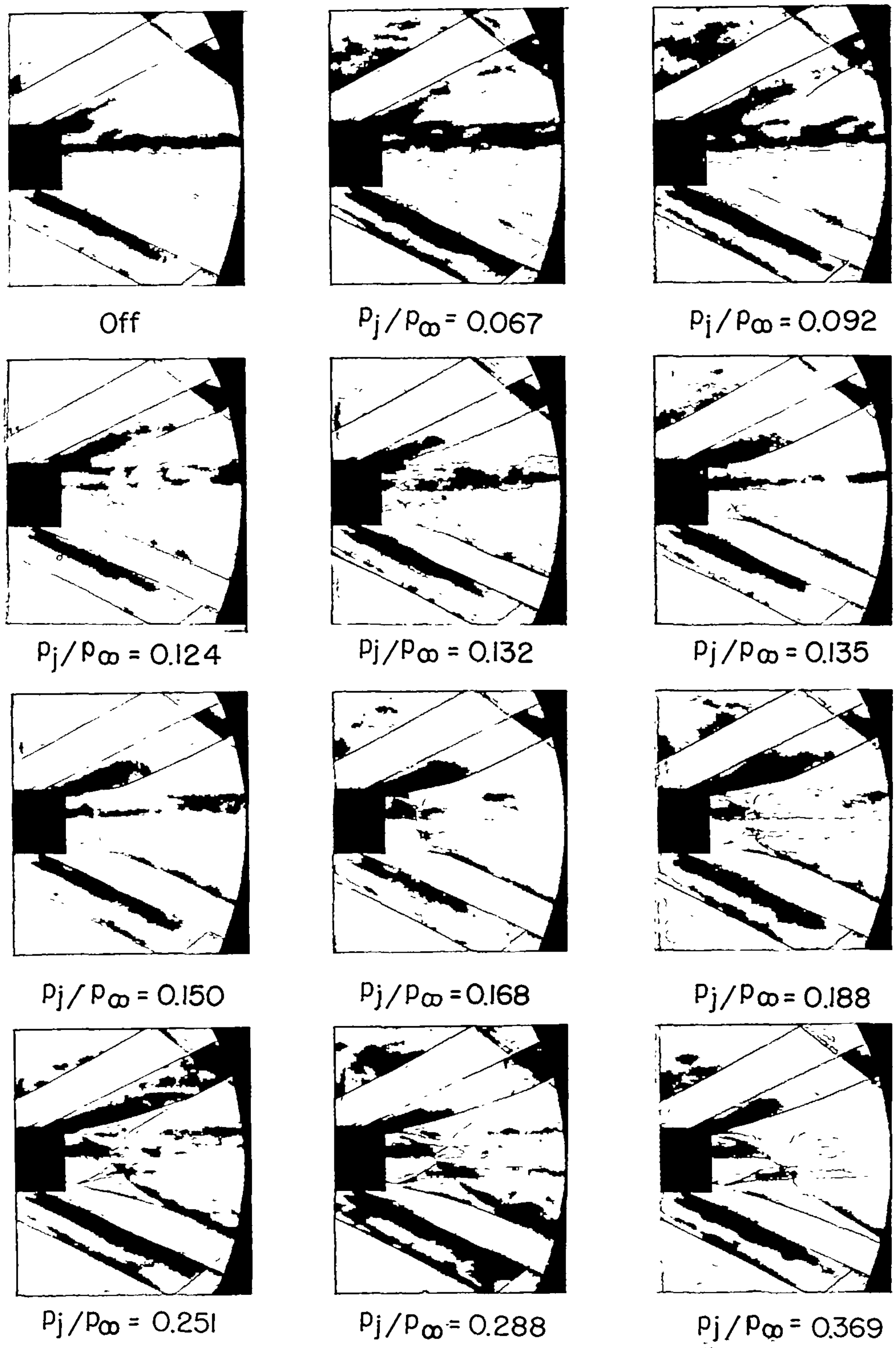

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Figure 8.- Schlieren photographs of a nozzle giving essentially isentropic flow with $M_j = 3.00$ and $\theta = 0^{\circ}$ at $M_\infty = 1.94$.

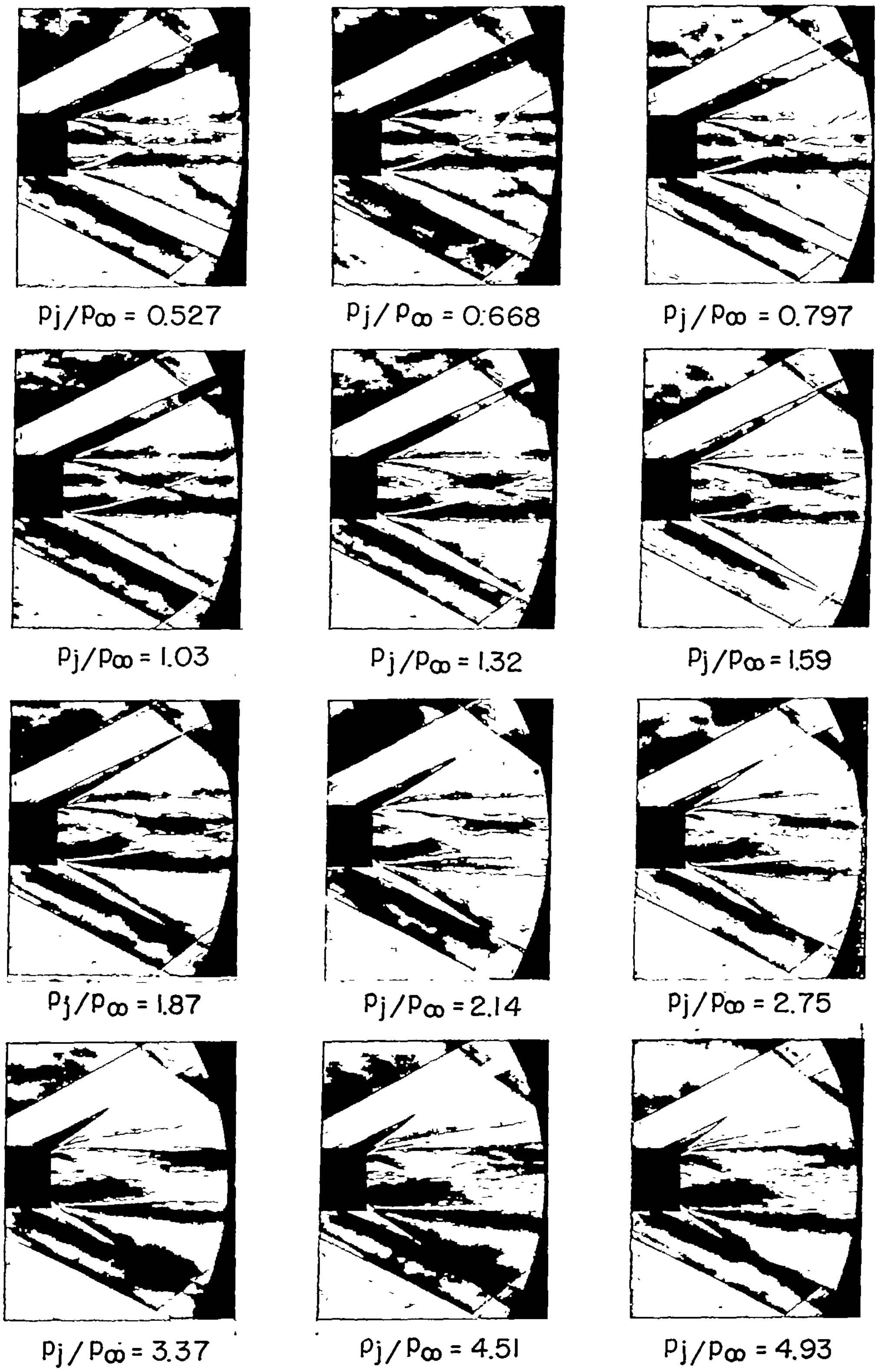

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Figure 8.- Concluded.